

## **Environmental Acoustics and Intensity Vector Acoustics with Emphasis on Shallow Water Effects and the Sea Surface**

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### **LONG-TERM GOALS**

To understand and predict key properties of the signal intensity vector field as it propagates away from an active sound source with emphasis is on shallow water propagation. These properties are in turn determined by properties of the sea bed, the sea surface, and bathymetry.

Advancement of current Navy capabilities will be in part realized through a better understanding of the environmental and acquisition geometry dependence (source depth, range, etc.) of the vector field in a shallow water environment.

### **OBJECTIVES**

This year our objective has been to investigate properties of the acoustic vector field within a waveguide as they are influenced by the environment such as the time-varying sea surface and sloping bathymetry. The objective necessarily involves measurements from Targets and Reverberation Experiment (TREX13) conducted in spring 2013.

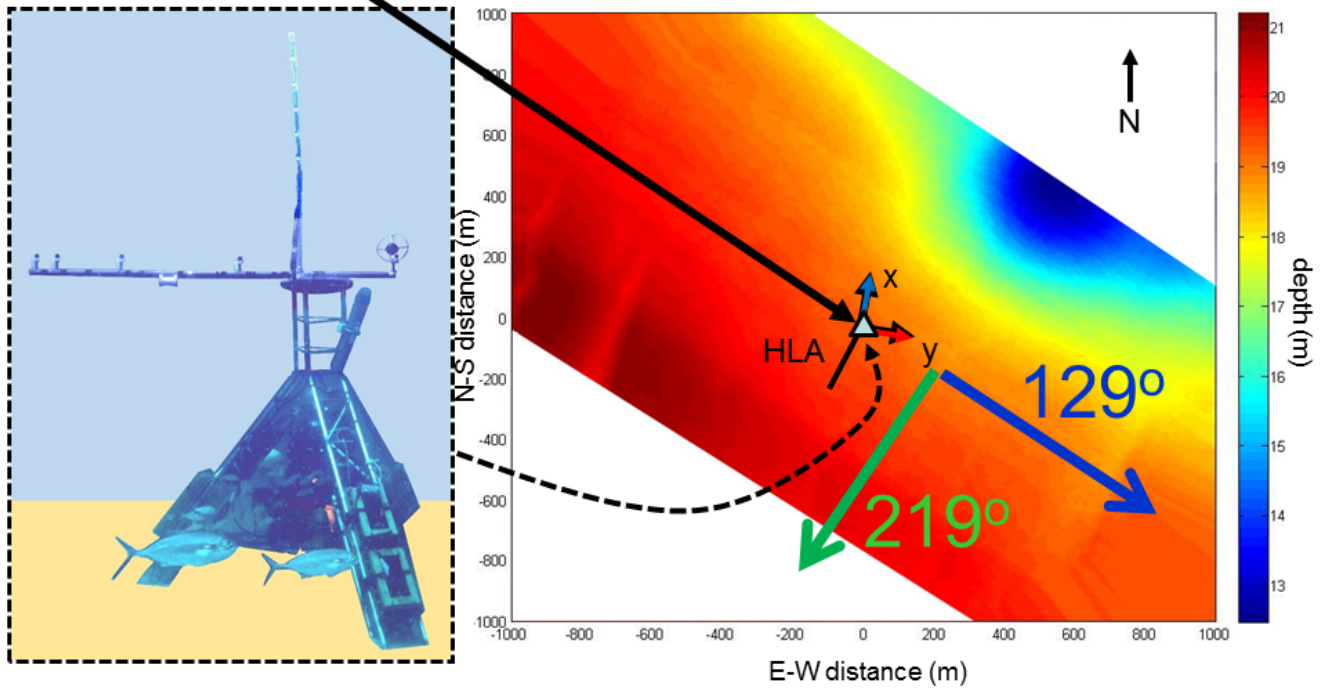
### **APPROACH**

Our approach revolves around the field measurement geometry we used for TREX13 which is shown (Fig. 1) for reference. TREX13 consisted of a series of shallow water reverberation measurements made of over a 5 km long track, detailed environmental studies of the sea bed and ambient noise, measurements of the sea surface directional wave spectrum at two locations, and propagation measurements involving vector and pressure sensing receiving arrays. The last two items represent contributions from this research program.

Bearing  $129^\circ$  constituted the primary look angle for the reverberation measurements; our team made related propagation measurements both parallel, and perpendicular to this primary look angle to study the role of directional waves on both reverberation and related propagation. These measurements were recorded on receiving station (known as MORAY) consisting of a combined pressure and vector sensor (4 channels), a 7-element vertical line array and a 4-element horizontal line array of pressure sensors as shown in Fig. 1 (left side).

To R/V Sharp, 5 km  
FORA source (ITC 2015)

## Basic Geometry for TRESX13



**Figure 1.** *Right side: Basic geometry of the TRESX13 experiment with focus on our measurements located 5 km from the R/V Sharp. Two key bearings 129° forming the primary look-angle for reverberation measurements using the sources co-located with the R/V Sharp, and the perpendicular direction 219°. Left side: underwater photograph of the MORAY tower housing vertical and horizontal line arrays and vector sensor.*

## WORK COMPLETED

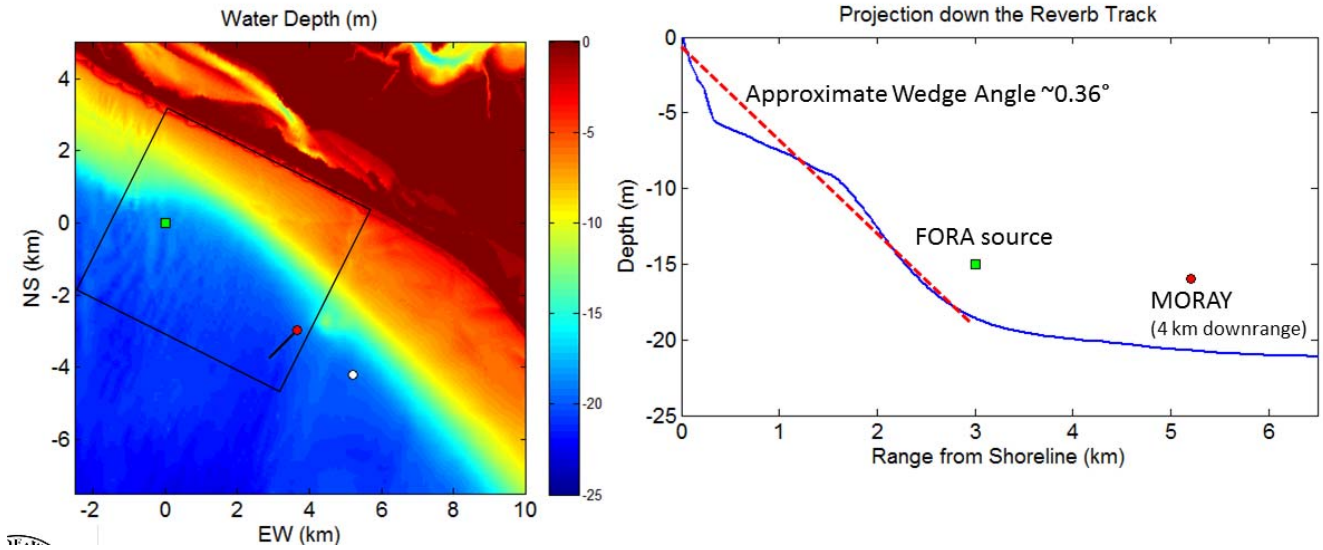
Our work this year on TRESX13 data, as carried out by the key team members, David Dall'Osto and Peter Dahl, is organized into two areas: (1) Horizontal refraction due to sloping bathymetry, (2) effects of the rough sea surface and subsequent stochastic horizontal refraction. Preliminary results were first discussed at the TRESX workshop in November 2014 (Indianapolis) and at the Acoustical Society of America meeting in May 2015 (Pittsburgh). A more finalized compendium of results is currently being worked on for a special issue on TRESX13 to be published by the *IEEE Journal of Oceanic Eng.* A summary of this work is given in the next section.

## RESULTS

### 1. Evidence of Horizontal Refraction

It is somewhat remarkable that the gradual sloping beach off coast of Panama City, FL (slope  $\sim 0.4^\circ$ ) is sufficient to produce an observable horizontally refracted path. Figure 2 (left side) depicts this slope with the position of the TRESX13 reverberation source shown in the green symbol relative to the MORAY receiver

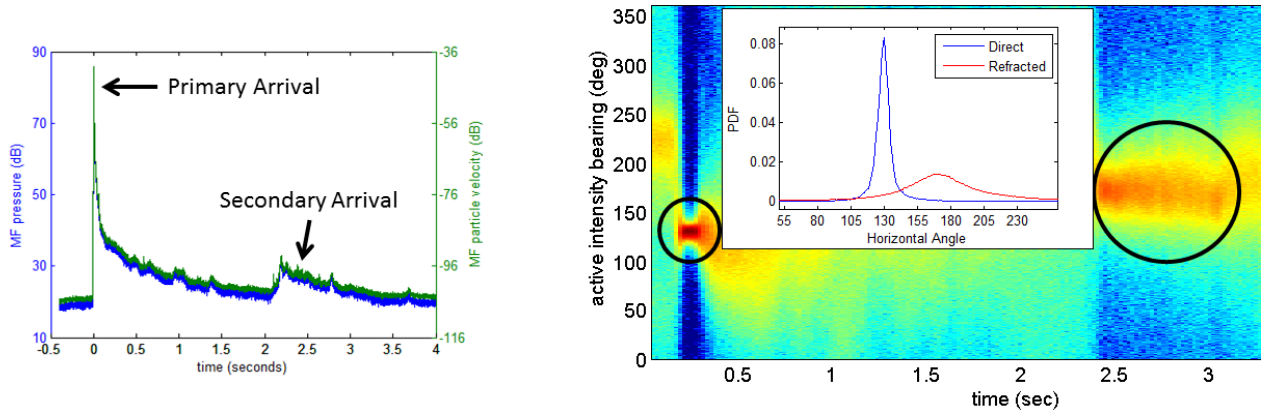
shown by the red symbol. Figure 2 (right side) shows the ranged-averaged bathymetry, that is along the bearing connecting the green and red locations; this averaged bathymetry is described by a slope of  $0.36^\circ$ .



**Figure 2. (left side) Bathymetry between the TREX13 reverberation source (known as the FORA source) depicted by green symbol, and the MORAY receiving array depicted by the red symbol. Relevant bathymetry is shown within the black box for which the shoreline, or land region, is located above the upper border of box. (right side) Range-averaged bathymetry defining the average slope of the beach within the box.**

Figure 3 (left side) shows a time series, averaged over 1 h period, of matched-filtered output from the TREX13 reverberation source as measured at the MORAY site with the vector sensor. The key point here is the direct pulse, shown with good pulse compression, is followed about 2.2 sec later by a secondary arrival. Note the dual scale for match-filtered pressure field (blue) and the particle velocity (green) measured by the vector sensor. The combination of pressure and particle velocity also provides an estimate of active intensity and arrival angle.

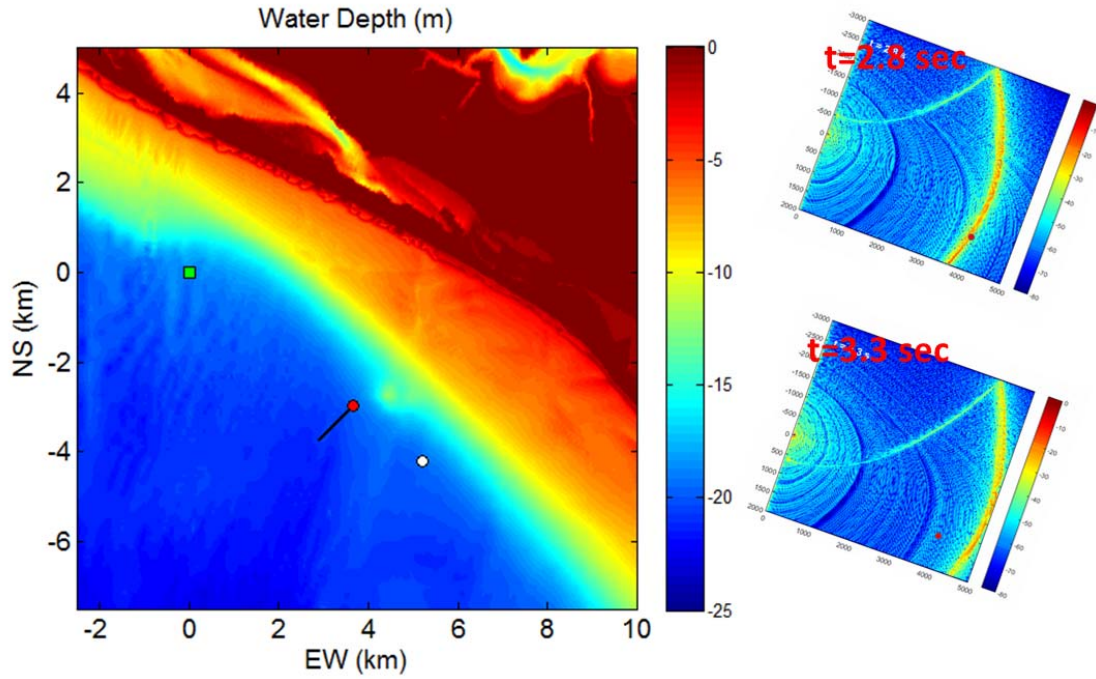
We postulate this secondary arrival is a result of bathymetric refraction [1] from the gently sloping bottom. The corresponding active intensity measured by the vector sensor (right side) shows the primary arrival angle is  $129^\circ$  (as expected according to experimental design) and the secondary arrival angle is  $172^\circ$  which is consistent with refraction. (Inset plot shows the distribution of active intensity which is considerably narrower for the stronger, primary arrival. )



**Figure 3. (left side) Time series, averaged over 1 h period, of matched-filtered output from the TREX13 reverberation source as measured at the MORAY site with the vector sensor. (right side) Corresponding active intensity measured by the vector sensory for which the primary arrival angle is  $129^\circ$  as expected by experimental design, and the secondary arrival angle is  $172^\circ$  which is finding that we have simulated. The secondary arrival is a result of refraction caused by the gentle sloping beach. Inset plot shows the distribution of active intensity which is considerably narrower for the stronger, direct arrival.**

The observations in Fig. 3 of primary arrival followed, a substantial time later, by a secondary arrival can be duplicated in our modeling. For this, we are informed by the work of Ballard [2] in which horizontal (bathymetric) refraction is solved using a parabolic equation (PE) in Cartesian coordinates. In particular for a given frequency and mode, the modal phase speed and imaginary part of the horizontal wavenumber, is assessed as a function of depth for the bathymetry shown box in Fig. 4 (left side). These results are used to populate the Cartesian space and subsequent refraction in this space is handled by the PE.

Figure 4 (right side) shows two snapshots of a broad-band simulation of the pulse (center frequency  $\sim 1$  kHz) transmitted from the FORA source. The MORAY receiving site is represented in each snapshot by the red dot. The upper snapshot corresponds to 2.8 sec after transmission representing the expected arrival for the primary arrival. The lower snapshot is 3.3 sec after transmission; here the primary arrival has gone past the MORAY receiver and following it is the weaker secondary or refracted arrival. This will reach the MORAY receiver at time 5.0 sec, or 2.2 sec after the primary arrival as shown in Fig 3. (left side).



**Figure 4. (left side) Bathymetry between the TREX13 reverberation source (known as the FORA source) depicted by green symbol, and the MORAY receiving array depicted by the red symbol. (right side) Two snapshots of a broad-band simulation of the pulse (center frequency  $\sim 1$  kHz) transmitted from the FORA source. The MORAY receiving site is represented in each snapshot by the red dot. The upper snapshot corresponds to 2.8 sec after transmission representing the expected arrival for the primary arrival. The lower snapshot is 3.3 sec after transmission; here the primary arrival has gone past the MORAY receiver and following it is the weaker secondary or refracted arrival. This will reach the MORAY receiver at time 5.0 sec, or 2.2 sec after the primary arrival as shown in Fig 3. (left side).**

These results are part of manuscript in preparation for the special issue in the *IEEE J. Oceanic Eng.* relating to TREX13. A similar approach, however, was also applied to the interpretation of the measurements of radiated noise from marine pile driving in Puget Sound, WA. Here, bathymetric refraction was observed on a measurement transect that was parallel to a sloping beach [A].

## 2. Horizontal Streamlines

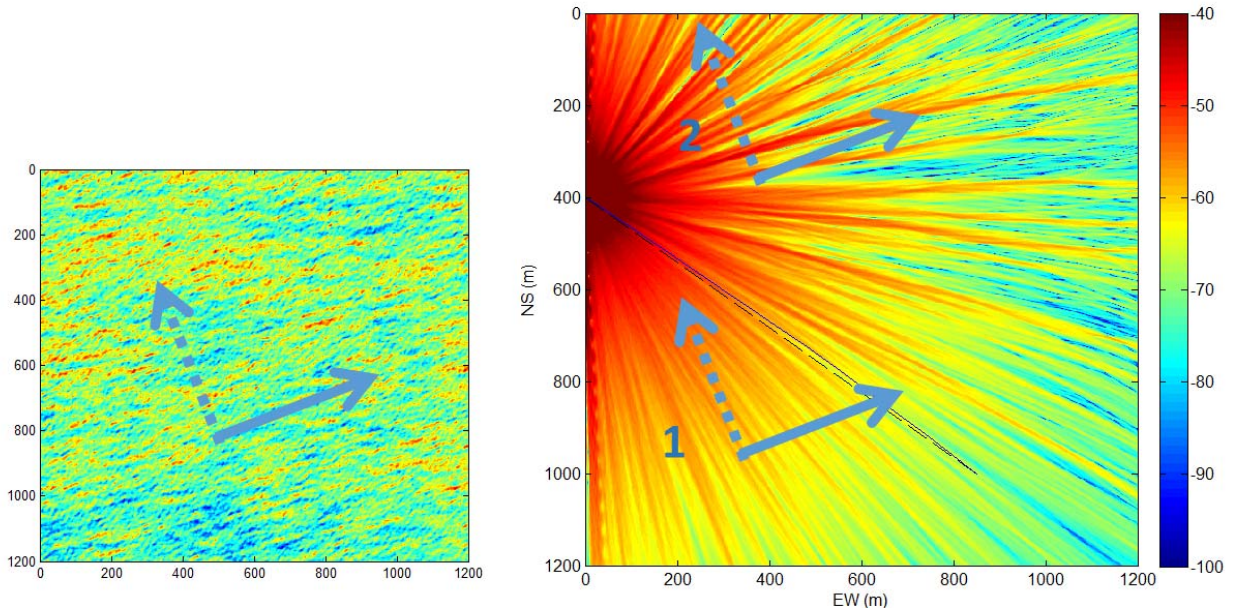
Figure 5 represents an extension of the above results to study the influence on rough surface propagation. This remains an active area of research on our part but it is worthwhile conveying these preliminary results. The left side is a single realization of the rough sea surface for which the rms waveheight is 0.15 m. The wave realization is based on the actual direction wave spectrum measured. The two arrows indicate directions nominally parallel (solid arrow) and perpendicular (dashed arrow) to the crests and troughs of the dominant sea surface waves.

The right side of Fig. 5 is display of modal amplitudes for a single mode at 1000 Hz, based on depth of 19 m.



The waveguide supports 10 modes at this frequency and this mode-6, a mode chosen because it and modes of higher order will have correspondingly steeper equivalent grazing angles with respect to the sea surface. (The grazing angle for mode 6 =  $12^\circ$ .) The modal amplitude field is plotted for a source at coordinates EW = 0 and NS = 400 m. The key observation made here is the significant difference in spatial variation undertaken by this mode that depends on propagation direction. For example, in region 1 the direction of acoustic propagation is nominally perpendicular to the wave crests and troughs – as if the acoustic field is propagating along a washboard.

In region 2 the propagation direction is more closely aligned with surface wave crests and troughs (or is perpendicular to the direction of sea surface wave propagation.) Region 2 produces considerable variation in modal amplitude associated with focusing and defocusing of the surface crests and troughs. Such focusing can actually produce a small degree of horizontal refraction in the as depicted by the dashed (non-refracted) and solid (refracted) streamlines associated with this mode. In addition to the effect focusing/defocusing has on the pressure field, it will also increase the level of reactive intensity in the horizontal plane similar to increases in vertical reactive intensity associated with multipath interference in shallow water [3].



**Figure 5.** (left side) a single realization of the rough sea surface for which the rms waveheight is 0.15 m. The wave realization is based on the actual direction wave spectrum measured. The two arrows indicate directions nominally parallel to the sea surface dominant waves (solid arrow) and perpendicular to these waves (dashed arrow). (right side) The amplitude of mode-6 (equivalent grazing angle =  $12^\circ$ ) for a 1000 Hz source located at coordinates EW = 0 and NS = 400 m. Arrows show the orientation of the surface wave field, and for region 1 the azimuthal angle is nominally perpendicular to the direction of wave propagation whereas for region 2 the azimuthal angle is nominally parallel to the direction of the surface wave field.

## **IMPACT/APPLICATIONS**

Our studies on the effects of the directional wave spectrum, have shown how directional waves can have a direct impact on reverberation in shallow water.

Our studies in vector acoustics have led to potential applications involving the detection of sources in shallow water, and geoacoustic related applications. Additionally these studies are to elucidating the role of gently sloping bathymetry, and associated bathymetric refraction, on reverberation for which the look angle is parallel to this slope.

## **RELATED PROJECTS**

The PI is advising PhD students Mr. Jeffrey Daniels, from the Acoustics Research Detachment (Bayview ID) Carderock Division, to study new vector sensing technologies, Mr. Alex Soloway to study underwater sound generated by explosions (see publication [B]), and Ms. Dara Farrell to study underwater noise from marine pile driving.

## **REFERENCES**

- [1] M.J. Buckingham, "Theory of three-dimensional acoustic propagation in a wedge-like ocean with penetrable ocean," J. Acoust. Soc. Am., 82 198-210, 1987
- [2] M. S. Ballard, "Modeling three-dimensional propagation in a continental shelf environment, J. Acoust. Soc. Am., 131 1969-1977, 2012.
- [3] D.R. Dall'Osto, P. H. Dahl, and J. W. Choi, Properties of the acoustic intensity vector field in a shallow water waveguide, J. Acoust. Soc. Am., 131 (3) 2023-2035, Mar. 2012.

## **PUBLICATIONS**

- A. P. H. Dahl, D. R. Dall'Osto, and D. M. Farrell, The underwater sound field from vibratory pile driving, J. Acoust. Soc. Am., 137 (6) 3544-3554, June. 2015 [published, refereed]
- B. Soloway, P. H. Dahl and R. I. Odom , Modeling explosion generated Scholte waves in sandy sediments with power law dependent shear wave speed, J. Acoust. Soc. Am., Express Letters, Sep. 2015. [published, refereed, in press September 2015]